INEEL/CON-99-00889
PREPRINT

Crack Growth Monitoring in Harsh Environments by Electrical Potential Measurements

W. R. Lloyd
W. G. Reuter
D. M. Weinberg

September 19, 1999 – September 22, 1999

Photonics East 1999 - Environmental and Industrial Sensing; Harsh Environment Sensors II

Crack Growth Monitoring in Harsh Environments by Electrical Potential Measurements

W. Randolph Lloyd, Walter G. Reuter, and David M. Weinberg
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, Idaho Falls, ID 83415-2218

ABSTRACT

Electric potential measurement (EPM) technology offers an attractive alternative to conventional nondestructive evaluation (NDE) for monitoring crack growth in harsh environments. Where conventional NDE methods typically require localized human interaction, the EPM technique developed at Idaho National Engineering and Environmental Laboratory (INEEL) can be operated remotely and automatically. Once a crack-like defect is discovered via conventional means, EPM can be applied to monitor local crack size changes. This is of particular interest in situations where an identified structural defect is not immediately rejectable from a fitness-for-service viewpoint, but due to operational and environmental conditions may grow to an unsafe size with continuing operation. If the location is in a harsh environment where periodic monitoring by normal means is either too costly or not possible, a very expensive repair may be immediately mandated. However, the proposed EPM methodology may offer a unique monitoring capability that would allow for continuing service.

INEEL has developed this methodology, supporting equipment, and calibration information to apply EPM in a field environment for just this purpose. Laboratory and pilot scale tests on full-size engineering structures (pressure vessels and piping) have been successfully performed. The technique is applicable in many severe environments because the sensitive equipment (electronics, operators) can be situated in a remote location, with only current and voltage probe electrical leads entering into the harsh environment. Experimental results showing the utility of the methodology are presented, and unique application concepts that have been examined by multiple experiments are discussed.

Keywords: electric potential measurement, crack growth monitoring, piping inspection, lifetime extension, plant safety, fracture mechanics, severe environments

1. BACKGROUND

Electric potential measurement (EPM)[a] has been in use for many years in fracture mechanics testing applications. Early uses of EPM focused on fatigue crack growth rate tests. Its use has expanded in more recent years to include stress corrosion crack rate testing and corrosion fatigue testing. EPM application to crack length monitoring for the standard J_{Ic} fracture toughness test was included in recent ASTM testing standards (ASTM E 1737-96).[1] EPM has received wide acceptance in the fracture mechanics testing community as a reliable method for assessing changes in crack length in two-dimensional laboratory test specimens (standard fracture toughness specimen geometries, including single edge notch and compact tension geometries).

The INEEL Fracture Mechanics Section has spent the last 15 years investigating the fracture behavior of structural materials using various experimental and numerical techniques. Surface cracked (three-dimensional) plate test specimens containing semi-elliptical cracks, in conjunction with the standard two-dimensional geometries, have been used to better understand the fracture process in full scale structures (Reuter et al.[2]). EPM has been employed in much of the testing, and a good understanding of the general capabilities of the EPM methods have been developed. This experience dictates that EPM can be quite useful beyond its conventional applications for crack length monitoring in standard test methods.

Many of the test techniques that employ EPM involve long durations with intermittent crack length monitoring, such as corrosion fatigue monitoring (weeks to months duration). This type of testing using EPM shows that it can be applied over long time spans to accurately monitor crack length(s). The EPM technique has also been applied over a wide range of temperatures in various test programs at INEEL. In all cases, with appropriate use of the reference voltage (see Donald and

[a] Also referred to more specifically as DC Potential Drop, DCPD, DCP, and the corresponding AC methods.

Ruschau[3]) to correct for temperature-dependent material resistivity changes, good correlation of EPM calculated crack length change with physical measurements has been found.

Based on the results of testing performed by the INEEL, a generally applicable method of crack length monitoring that can be applied to structures, in the field, subjected to harsh environments, is proposed. It is cost effective because it can be applied without additional plant or system loop shutdowns, is generally impervious to low or high temperatures,[b] and can be performed remotely (away from immediate human hazards).

2. METHODOLOGY AND EXPERIMENTAL VERIFICATION

The basic technique is that of multiple cycle, DC current reversing, electric potential measurement as described by Donald and Ruschau[3] and Catlin et al.[4] The technique and associated methodology as described herein is intended for application in the area of plant life extension, a very important area in today's cost-cutting operations environment. It is not intended to replace the more conventional NDE methods of *detection*, but as a way to prolong useful life of plant components through *monitoring* of sub-critical crack-like defects discovered by traditional inspection methods.

In many cases, mandated periodic inspections are very costly due to required plant shutdowns, and in some cases required insulation removal, cleaning of surfaces, and so on. Specifically, there are many instances of low temperature piping and vessels in the petrochemical industry. These systems are encased in thick insulation due to very low (or very high) operating temperatures. Normal inspection requires plant or loop shutdown to prevent ice formation when insulation is removed. These inspections usually require the services of highly trained inspectors as well. If a defect is found it is analyzed to determine how it effects structural integrity. If the crack is of a size that is not large enough to dictate immediate repair or replacement, the unit may be placed back in service, possibly with a decreased inspection interval. The shorter interval may be specified, for example, if the crack were relatively large, say approaching the maximum allowable length that would require immediate repair or replacement.

This methodology provides a means to reassess the identified crack at will, while the plant is on line and at operating temperature. Subsequent removal of insulation (as would be required for a UT exam) that leads to immediate build-up of thick ice layers is not required. Together this can lead to reduced inspection costs, reduced plant downtime, and extended component lifetime.

2.1. Crack Length Change and Detection

The nature of EPM measurements is such that the direct measurement of the electric field at selected points in a cracked structure correlates with crack length change, not absolute crack length. There is a large amount of literature that discusses the mathematical foundations of the EPM method (for example, Johnson[5]), and describes the application of EPM to common "two-dimensional" test specimens. The same general fundamentals apply to the three-dimensional case of interest. However, closed form mathematical solutions are not available to directly correlate crack length change with electric potential change. While this may seem to be a significant impediment, empirical studies at INEEL show otherwise.

An earlier INEEL study of crack growth initiation events, and the corresponding forces, crack opening, stress intensity distributions, etc., for various surface crack geometries was yielding apparently irregular results. Although high strength steels were used, crack initiation prior to maximum applied force was suspected. Acoustic emission (AE) data suggested that this was the case, but could not definitively quantify it. The EPM technique (in this case, the DC current reversing method) was applied to a number of specimens. AE, and conventional force and displacement measurements were also made simultaneously, and did confirm earlier-than-expected crack growth initiation. It also confirmed that a very substantial amount of stable crack extension was occurring in many specimens prior to actual specimen failure by unstable crack extension.

With appropriate modifications to the software of the EPM data acquisition system, multiple voltage probe points were incorporated, and high rates of crack length measurement (several per second) were achieved. Another experimental study was undertaken to explicitly look at the subcritical stable crack extension, and crack shape evolution of surface cracks subjected to tension and bending forces. Several of the high strength steel specimens of varying sizes and crack geometries

[b] With appropriate selection of lead wires and insulation

were instrumented and tested. Voltage probe leads were attached to the front (cracked) face of the plate-type specimen about 2 mm above and below the crack plane at various positions along the length of the crack.

The test procedure included fatigue precracking of the specimens to the desired starting crack size. The specimens then received between one and five sequences of monotonic loading to achieve a small amount of stable crack growth followed by load reduction and fatigue cycling to mark the extent and location of subcritical crack growth.

An example of the fracture surface of one such specimen is shown in Figure 1. The fatigue precrack, three cycles of monotonic loading (final cycle resulted in specimen failure), and two bands of cyclic fatigue marking are readily apparent. Four channels of EPM voltage data were collected throughout the entire test sequence. EPM response varied according to voltage probe location, but was indicative of localized crack extension near the probe wire mounting position. A plot of EPM voltage measurements taken at the centerline position (nominal maximum crack depth) during each of the three monotonic loading sequences is shown in Figure 2. The difference between the EPM values at the end of one loading and the start of the subsequent one is due to crack growth (marking) during the fatigue cycling phase. These results are typical of the specimens tested, including both the high strength steel (D6-aC, 1600 MPa yield strength) and a medium strength structural alloy (ASTM A 710, 450 MPa yield strength). Note that a relative EPM voltage increase of approximately 5% corresponds to a local increase in crack length of about 5%. This empirical correlation was found to be consistent for all of the cracks of varying depth (a/t) and moderate to low elliptical aspect ratio (a/c).[c]

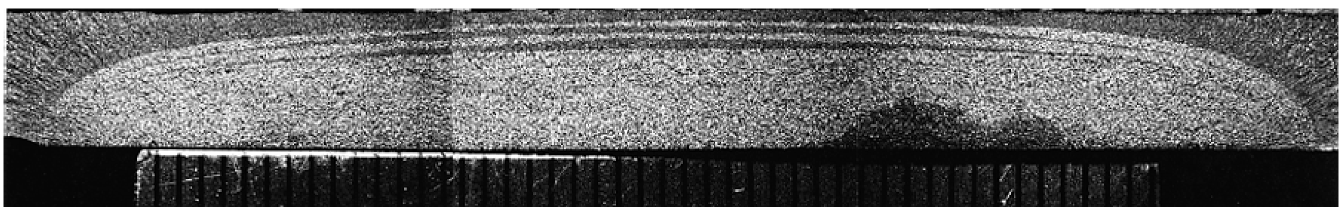

Figure 1. Fracture surface of D6-aC steel specimen with crack growth from multiple loading and fatiguing cycles.

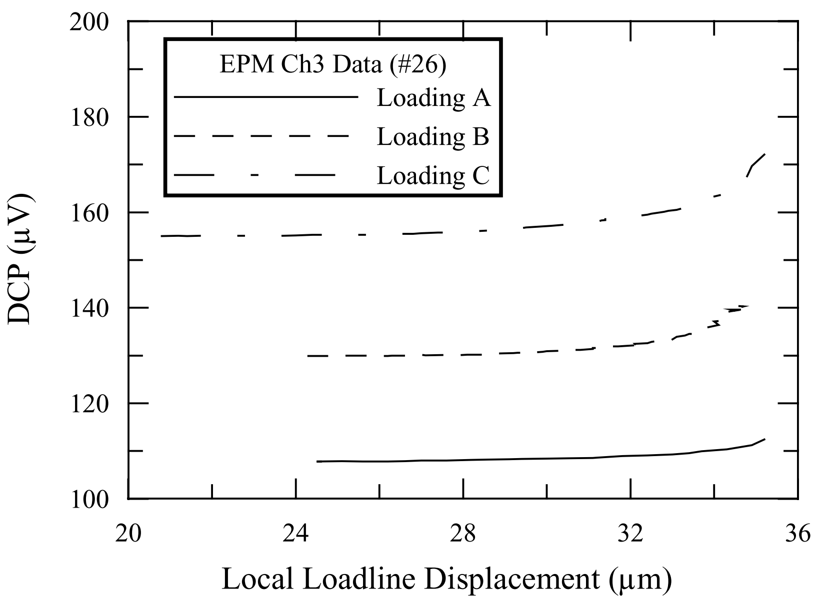

Figure 2. Representative EPM data from the test specimen shown in Figure 1. Channel 3 is connected near the horizontal crack centerline.

2.2. Voltage Probe Location and Reference Voltage Measurement

In another test program, large pressure vessels were hydrostatically tested to failure/leaking to investigate crack growth behavior in actual engineered structures. Several vessels, removed from service after cracks were detected during routine inspections, were acquired and assessed. Most of these vessels contained various internal cracks. One vessel contained a longitudinal crack on the inner surface that was between 50 and 80% of the wall thickness (17 mm) and was over 2 m long. UT examination was applied to map the crack depth along its length. The deepest point (as indicated by UT exam) was expected to be the location of first crack initiation, and guessed to be the point where the crack would eventually penetrate the wall thickness. It would be difficult to apply voltage and current leads to the inner surface (requiring a pressure-proof feed through and no way of verifying suspect

[c] for semielliptical cracks in plates: a ≡ maximum crack depth, c ≡ crack length on surface, and t ≡ plate thickness.

instrumentation behavior after the vessel was sealed for testing). Instead, the current and voltage probe leads were mounted on the outside of the vessel, spanning the plane of the internal crack. As expected, the resultant EPM sensitivity was reduced somewhat, but very adequate data were collected during the test. EPM probes, located at expected crack growth regions based on UT results, were very well positioned as it turned out. The point of eventual leakage was within 7 mm of the plane of one of the probe pairs. Figure 3 shows two of the probe pair leads located on the vessel outer surface, adjacent to a longitudinal weldment. The point of leakage (first wall penetration) is near the left side probe pair (“A”) in the figure. Figure 4 shows the EPM voltage data for the three active probe pairs (corrected using a reference voltage probe pair). The data labeled “A” were near the point of eventual leakage. “B” data were approximately 50 mm to the right of “A” as shown in Figure 3, about 45 mm from the leakage point. “C” data were collected about 150 mm down the length of the crack (parallel to the weldment), to the left of “A.” Metallographic sectioning of the crack (post-test exam) confirmed a moderate amount of crack extension near the “B” position and very little crack extension near “C.” This metallographic exam produced additional information that was very beneficial to this investigation. The monitored area of the crack in the pressure test had many interesting details. These included a large amount of localized length variation, highly bifurcated growth paths, and close proximity to the interface of two materials with different electrical properties. Even with these complicating factors, the EPM methodology was successfully applied to detect growth initiation and subsequent extension to the point of wall penetration.

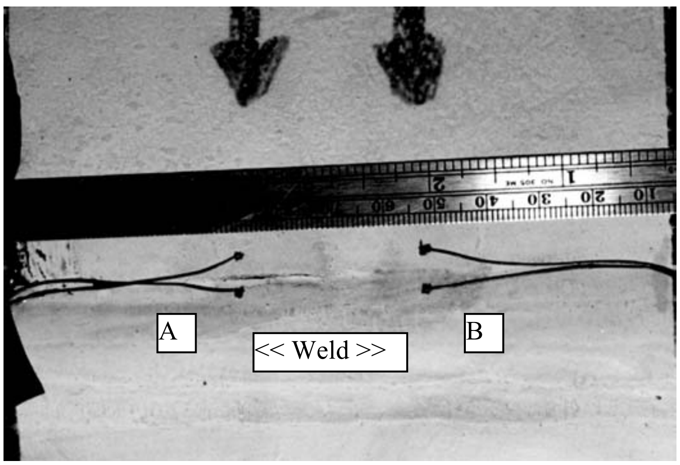

Figure 3. Location of EPM leads “A” (left) and “B” (right) at weld boundary on outside of pressure vessel. Initial leakage just to right of “A.”

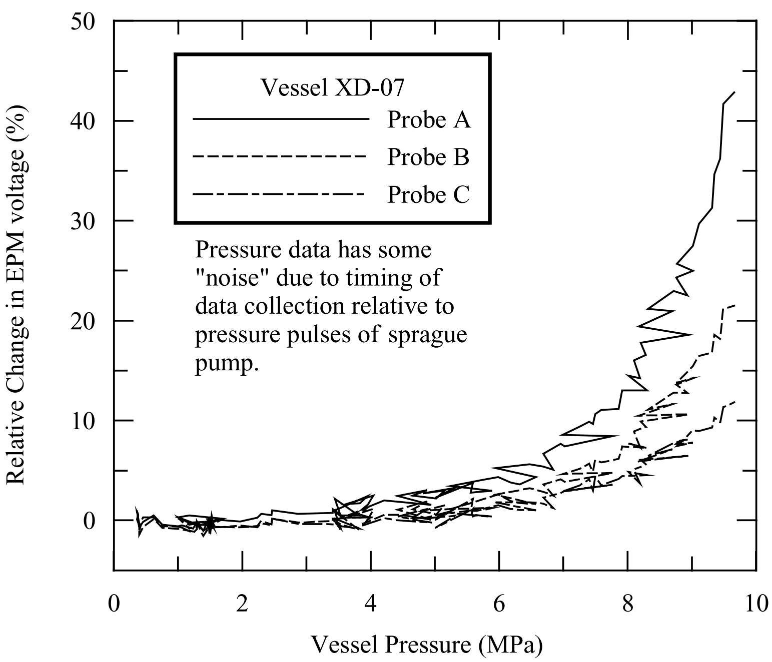

Figure 4. EPM data from vessel test showing difference in crack growth at different positions along crack length.

In the case of this cylindrical vessel test, there are also multiple current paths. This is also the case in many engineered structures. The reference voltage concept was used successfully for the test of the pressure vessel. While a significant change in current path during the test was not anticipated, a reference voltage probe lead pair was placed on the approximate electric field symmetry line between the two current connection points. The probe points were placed in a location away from the crack plane where the current path should not be altered by crack growth. The pair was mounted about half way between the crack plane and one current input point. In this way, current across the crack plane at the measurement points could be normalized in case there were current path variations during the test. This general approach has been applied to other structures tested by INEEL with EPM instrumentation, including 350 mm W-section I-beams with cracked flanges and webs (see Gentilcore[6]).

Even if significant current path changes happen to occur in between consecutive measurements, the use of the local reference voltage probe data will provide an effective correction. The current monitoring reference voltage and the initial EPM data voltages taken at a known crack length (from standard NDE crack sizing method) can be used to effectively normalize channel voltages to 1.0. All subsequent measurements are then processed to yield a relative change percentage from the initial value of 1.0 for each of the data channels.

2.3. Time Variation of Measured Data and Repeatability

Time variations of the data acquisition system has been investigated to some extent. Several specimens were instrumented and periodically retested at varying time intervals (so far up to several days between tests). The acquisition equipment was disconnected from the specimens and shut down in the interim. Maximum corrected (using the reference voltage procedure) EPM values show maximum deviations from the average value (typically 20 or more samples) of less than ±0.10%, and typical sample maximum deviations of ±0.04%. Adjusting EPM scanning parameters and performing multiple measurements over a short time period could reduce this noise factor even more. Referring to the previous example, it is seen that voltage increases due to actual significant crack growth of about ten, to more than 50 times this maximum error band would be typical in an actual monitoring scenario.

A specific EPM test was run on an A710 steel surface cracked plate specimen, and yielded the following results. Twenty-five EPM measurements were taken on each of four voltage acquisition channels (three active and one reference) over a three hour period. At about 45 minutes elapsed time, the system was disconnected and shutdown for approximately one hour. The measured voltages (through preamplifiers set at gains of 20,000x) were normalized by the "per channel" overall average voltage, and then by the reference channel voltage measurements. A "perfect" result in this case would have all channels reading 1.0000 for every measurement. The sample in this case contained 75 active channel values. For this test the resultant average deviation was ±0.024% and the standard deviation was 0.031%. The voltage deviations that are of significance in the EPM monitoring scenarios will typically be in the 1% to 5% range – well above a conservative system resolution capability of 0.10%.

3. APPLICATION OF THE METHODOLOGY

3.1. Investigation and Set-Up

The process begins when a subcritical crack is discovered. This discovery may occur during a routine system inspection using normal NDE methods, or may be due to an inspection following a leak or failure of a similar structure. It may also have been detected in an initial pre-service inspection, but was of a small size and deemed "not rejectable" by the applicable codes. Regardless of the method of discovery, a crack-like defect is found to exist. It is assumed this crack can be sized with reasonable certainty (at least to the accuracy of the fracture mechanics assessment of structural integrity and/or the capability of the NDE technique). In normal practice, a pressure vessel code or standard would be consulted and a structural integrity assessment ("safe" or "not safe") would be made. In the case of a crack being "safe," the system may be returned to service, possibly with reduced operating stresses, altered process temperatures, and/or reduced inspection interval. It is in this case of a discovered crack that is of a "safe" size where this methodology can be helpful. It allows an arbitrarily short inspection interval with minimal expense, reduced inspector hazard, and accuracy typical of the best NDE methods (approximately two percent of the plate or wall thickness).

In the case of a relatively simple crack and structure geometry, standardized current lead locations and voltage probe attachment locations may be selected. Additional calculations and/or engineering judgement will have to be applied in the case of more complex crack geometries, or more complex structure shapes (such as varying wall thickness, nozzles, etc.). The number of voltage probe pairs required to sufficiently characterize the crack growth must also be established. The number and spacing are determined by a number of factors, including crack length, crack depth, criticality of the crack location, and others. Once the appropriate locations are determined, the lead wires are attached by suitable means.

Resistance welding of voltage lead wires, directly to the structure surface, has been proven to work well in experimental studies at INEEL. Small studs for current lead attachment can be attached with a resistance stud welder or by conventional welding or brazing methods. The fine gauge of the voltage lead wires and possibly delicate nature of the connections may be troublesome for long term monitoring. Redundant duplication of voltage leads, and potting or bonding the leads to the structure surface will minimize the likelihood of system failure. This, in turn, reduces the probability of a plant shutdown to remove insulation, reinstall lead wires, and recalibrate for the crack length at that time.

The leads are fed away from the crack area by a suitable electrically shielded cable. An environment-proof connector (standardized for the facility with multiple monitoring sites) and cap will terminate the lead cable, and facilitate connection of the portable monitoring station. The connector may also contain a site-unique identification resistor circuit allowing for automatic identification of the particular monitoring location within the site. Initialization parameters and past data for the location can be automatically recalled when the monitoring system is connected. This greatly reduces the chance of operator error in manually selecting the wrong data record for a particular location. This automatic identification feature also speeds up the system set-up for a monitoring scan. When the operator connects the system, it automatically detects the location. The system then informs the operator what the system settings should be (possibly fully automated in a production system). It also recalls the database for that location for comparison and automatic assessment of crack size changes and, very importantly, crack size change rates.

3.2. Baseline Data Collection

Once voltage probe leads and current leads are attached and electrical continuity is verified, a baseline calibration is performed. This involves connecting the monitoring system and adjusting input current and preamplifier gains to optimal ranges. A record for the specific location is also created in the site database. This database record will contain all location information, the actual monitored data, and information needed to make real time structural integrity assessments. These assessments, based on measured crack size and the applicable codes or methodologies, can be simple or complex, and may provide immediate warnings if any monitored or calculated parameters are outside of normal operating limits.

Once the system is connected, parameters are set, and correct operation is verified, baseline EPM readings are collected. These measurements should be taken with the system in its normal operating condition (stress, pressure, temperature, etc.). This will avoid the possibility of calibrating the measured voltages to an effectively smaller crack due to crack closure effects. These measured voltage values are normalized by the reference voltage and saved to the database along with the known crack size(s) as determined by the conventional NDE inspection. Subsequent voltages can then be compared and crack size changes can be estimated.

3.3. The EPM Monitoring Process

Plant system operating knowledge and fracture mechanics analysis of the crack when it is discovered are used to make an initial estimate of crack growth rate and mode of crack growth, e.g. stress corrosion cracking. This knowledge, combined with knowledge of the initial crack size, can be used to determine the required monitoring intervals. These intervals can be quite frequent, since subsequent monitoring inspection only takes the order of minutes at each location. The low cost of inspection, without interruption of plant operation, allows very conservative inspection intervals to be applied at the outset. The intervals should be relatively frequent, especially in the case of uncertainty about the crack growth mechanism. Frequent monitoring can give accurate crack growth rate information, which, in turn, can be used to re-establish an appropriate monitoring interval.

The actual EPM monitoring procedure is simple. The portable monitoring system is taken to the location and plug-connected to the test leads. The operator activates the monitoring system, and data is collected for a period of a few minutes. Automatic system check features will notify the operator of monitoring faults, such as a broken lead wire or unexpected changes in EPM voltage. If monitoring data collection terminates normally, the data are saved to the monitoring system local copy of the database. Checks and comparisons, designated by the systems engineer for that location, are applied and the system operator is immediately notified of any abnormal conditions. These conditions may be things such as excessive crack growth rate, unexpectedly large crack size, or crack size approaching a design limit. This information can then be passed back to the system engineer for further fracture mechanics-based analysis (where the specific analysis is not built in to the monitoring system).

3.4. Fracture Mechanics Analysis

Engineering judgement and sound fracture mechanics analysis of fatigue, stress corrosion, etc. must be employed to determine the initial inspection interval using the EPM system. Once several inspection cycles have been performed, the EPM data will provide actual crack size as a function of time or plant system cycles. This information can then be used to verify the crack growth rate model being used, and adjust the inspection interval to ensure that the crack does not grow beyond the specified size limit in between inspection cycles. Especially early in the inspection cycle, such frequent measurements can be employed to verify the crack growth model being used. The measured (actual) crack growth rates can be compared to model predictions, and model parameters can be tuned to match the observed rates for improved predictive capability.

3.5. Monitoring System Optimization Using Finite Element Modeling

This application of the EPM technique for plant system monitoring is still under investigation. The methodology has been proven functional in several structural applications and in laboratory test specimens. The complex case of, for example, an arbitrarily oriented, non-planar crack with an irregularly shaped crack border in a non-uniform structural geometry has not been thoroughly investigated. However, experimental results from the pressure vessel test discussed in Section 2.2 dictate that these conditions can be monitored with reliable results. Modern finite element modeling (FEM) capabilities and greatly improved computational resources will help make this problem more tractable in monitoring situations. The FEM model will provide the information necessary to accurately correlate local crack length to the measured EPM voltages. Such a linear electric potential problem is relatively simple to run using commercially available FEM packages and modern automatic meshing applications. In the case of engineered structures, the mesh generation program can take structural drawings in electronic form as input. Therefore, the modeling of complex cracks in complex geometries is not out of reason. This is especially true in the case of a costly structure or plant component whose service life can be safely extended using this technology.

A FEM model, such as the one described, may provide a number of benefits. The electric potential field at the accessible surface of the cracked structure can be calculated. Small changes in crack size can be applied in the FEM model and the resultant electric field gradients can be determined. Similarly, the current source/sink locations can be altered and the resultant fields calculated. This information can be used to optimize the monitoring lead locations.

The current leads can be positioned to provide maximum electric potential over the region of interest. This minimizes the monitoring system's current source amperage requirements. The voltage probe leads are optimally positioned where the change in potential with changing crack size is the highest that is possible, without locating the probe points in locations where local spatial field gradients are high. This gives the monitoring system maximum signal-to-noise ratio while also maximizing the system's sensitivity to crack size change.

In the case of a complex crack geometry, where the crack may not grow in a self-similar shape, combined FEM modeling and an array of probe points may allow a more accurate map of crack shape change to be determined. This approach has not been investigated, and it may turn out that a unique solution for crack shape cannot be found without some additional supporting data. However, this type of FEM modeling exercise may lead to increased knowledge about the application of EPM monitoring, in turn leading to improved estimation of crack shape changes.

3.6. Precautions in Usage

There is one particular case where the application of this EPM methodology may be unwise. That case is in the situation where active corrosion is occurring and the corrosion products are conductive. In this case, current shunting between the opposing crack faces will cause the EPM monitoring to calculate an artificially shorter crack. In the case where EPM monitoring is the only option, and such corrosion is expected, there may be some possibility of successful application. If, under similar operating conditions (pressure, stress, etc.) the EPM-measured crack length is found to significantly decrease, there is sure indication of current shunting at the crack. While this does not give a reliable crack size indication, it definitely indicates that the measurements are not reliable. Another approach which may be used in some cases is system stress cycling. If the applied stress or pressure can be cycled a bit outside of normal system operating ranges, the corrosion products may be disrupted or dislodged from the crack volume, and a corresponding immediate change of crack size would be noted. This would not be a normally advised procedure since other plant system damage could be incurred during the stress cycling. It may be a more viable solution in this special case if the monitored component can be effectively isolated from the rest of the plant during the stress cycling.

The EPM monitoring technique would not be applicable in the related case of a highly conductive (order of the structural material) solution in contact with the cracked surface. Although, in theory, if there is some difference in conductivity a crack length change can be detected, the practical application would be very suspect. Very large currents may be required to achieve an acceptable signal-to-noise ratio, and minor changes in fluid conductivity, not accounted for by the reference voltage measurement, may cause significant and unknown errors in the crack size calculation.

4. CONCLUSIONS

A new monitoring system and corresponding methodology has been described that is generally applicable to crack size monitoring in an industrial plant environment. The benefits of this methodology are many. Most significantly, crack size monitoring can be achieved at shorter time intervals, with greater or equivalent accuracy than conventional NDE techniques, and at much lower cost in many cases. This can all be achieved without additional plant or process disruptions, further reducing costs while safely extending the operating lifetime of the plant system or component.

The methodology is uniformly applicable over a wide range of temperatures. The monitoring system operator can be effectively isolated from the harsh or unsafe environment by extending the probe lead cable to a suitable safe location. The monitoring system operator does not need special skills or expertise. Basic computer literacy and the ability to connect the monitoring system cable to the connector on the component monitoring lead is all that is required.

Fracture mechanics assessment methodology can be applied to determine component or structural safety with greater reliability and less conservatism due to improved crack sizing accuracy. This leads to extended component or system operating lifetimes while maintaining operational safety.

To summarize, the EPM crack monitoring methodology described has the following features:

- Lower overall cost – dollars and time
- No plant or system operation disruption after initial set-up
- Efficient and effective lifetime extension through short time interval monitoring and application of fracture mechanics analyses
- Better safety and comfort of the monitoring system operator compared with traditional NDE inspection
- Minimal training of technician to operate the monitoring equipment

ACKNOWLEDGMENTS

This work was supported through the INEEL Laboratory Directed Research and Development Program under DOE Idaho Operations Office Contract DE-AC07-94ID13223.

REFERENCES

1. "Guidelines for Direct Current Electric Potential Determination of Crack Size," in Standard Test Method for J-Integral Characterization of Fracture Toughness, Designation E 1737-96, Appendix A5 *, American Society for Testing and Materials Annual Book of Standards*, **Vol. 3.01**, West Conshohocken, PA, 1997.

2. Reuter, W. G., N. C. Elfer, D. A. Hull, J. C. Newman, Jr., D. Munz, and T. L. Panontin (1997), "Fracture Toughness Results and Preliminary Analysis for International Cooperative Test Program on Specimens Containing Surface Cracks," *Fatigue and Fracture Mechanics: 28th Volume*, **ASTM STP 1321**, J. H. Underwood, B. D. Macdonald and M. R. Mitchell, Eds., American Society for Testing and Materials, 1997, pp. 146-165.

3. Donald, J.K. and J. Ruschau (1990), "Direct Current Potential Difference Fatigue Crack Measurement Techniques," in *Fatigue Crack Measurement: Techniques and Applications*, K.J. Marsh, R.O. Ritchie, and R.A. Smith, Eds., EMAS, June 1990.

4. Catlin, W. R., D.C. Lord, T.A. Prater, and L.F. Coffin (1985), "The Reversing D-C Electric Potential Method," *Automated Test Methods for Fracture and Fatigue Crack Growth*, **ASTM STP 877**, W.H. Cullen, R.W. Landgraf, L.R. Kaisand, and J.H. Underwood, Eds., American Society for Testing and Materials, Philadelphia, PA, pp.67-85, 1985.

5. Johnson, H.H. (1965), "Calibrating the Electric Potential Method for Studying Slow Crack Growth," *Materials Research and Standards*, **5** (9), September 1965, pp. 442-445.

6. Gentilcore, Michael L., *Ductile Tearing of High-Toughness Steel Members*, Thesis (Ph.D.), DISS 1996 G338D – Lehigh University, 1996.